# Revisiting Humidity Ramp Protocols for Assessing Human Heat Tolerance

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**Abstract** (248 words)

**Background**: Humidity ramp protocols are widely used to determine human heat tolerance, yet it remains unclear how the rate and duration of environmental changes affect the apparent inflection in core temperature ($T_{cr}$). This study integrates theoretical modeling and empirical trials to examine how the temporal structure of humidity-ramp protocols affects the accuracy of estimated critical environmental limits (CELs).

**Methods**: A first-order model was developed to describe $T_{cr}$ response to stepwise changes in equilibrium core temperature ($T_{cr,eq}$) determined by ambient humidity at a fixed dry-bulb temperature. Analytical solutions were derived for discrete humidity steps of duration $\Delta t$, and sensitivity analyses were conducted across physiologically plausible time constants ($\tau$). Fourteen healthy young males (23.5±1.8 yrs) completed two randomized trials in a 42 °C heat chamber: 1) *Slow-ramp*: 4-hour equilibration at 40% RH followed by +6% RH/hour for 2 h, then +3% RH/hour (40–61% RH); and 2) *Aggressive-ramp*: 30 min equilibration followed by +2% RH every 5 min (28–88% RH). Rectal and skin temperatures, heart rate, and perceptual ratings were recorded continuously.

**Results**: When $\Delta t/\tau \ll 1$, residual disequilibrium between $T_{cr,eq}$ and $T_{cr}$ accumulates, producing accelerated rises in $T_{cr}$ and premature CELs. Longer dwell durations (≥ 1 hour per step) allowed near-equilibrium responses, yielding physiologically valid thresholds. Empirically, shorter ramp durations shifted apparent CELs downward by 3.4±1.9 °C.

**Conclusion**: Dynamic lags from short dwell intervals lead to the systematic underestimation of heat tolerance. Reliable determination of CELs requires either prolonged steady-state exposures or dynamic correction models validated against such conditions.

**Keywords**: humidity ramp; thermoregulation; rectal temperature; critical environmental limits; heat tolerance; prolonged exposure

## Key points

- Humidity-ramp protocols are widely used to identify the transition from compensable to uncompensable heat stress, but their reliability is fundamentally constrained by the body's thermal response time.
- A first-order dynamic model demonstrates that the ratio of step duration ($\Delta t$) to the physiological time constant for core temperature equilibration ($\tau$) determines whether true steady-state conditions are achieved.
- When $\Delta t/\tau \ll 1$ (e.g., 5–10 min steps), dynamic lags accumulate between environmental and physiological states, producing premature inflection points that systematically underestimate human heat tolerance.
- Empirical data confirm that conventional short-duration ramps fail to capture true critical limits, while longer ramps ($\Delta t \geq 1$ h; $\Delta t/\tau \approx 0.3$–$0.5$) approach equilibrium but remain less robust than steady-state exposures.
- Accurate determination of critical environmental limits requires either prolonged steady-state exposure or validated dynamic correction models; uncorrected ramp protocols should not be used as stand-alone methods.

## Introduction

As global temperatures rise and extreme heatwaves become increasingly frequent, intense, and prolonged (Rahmstorf and Coumou 2011), understanding the physiological limits of human heat tolerance has never been more crucial (Pandolf 1997; Taylor 2014; Bouchama 2025; Wang 2025a). A central challenge is defining the critical environmental limits (CELs)—combinations of ambient temperature and relative humidity (RH) beyond which the human body can no longer maintain thermal equilibrium. Crossing these limits results in uncompensable heat stress, characterized by a rapidly elevation in core temperature ($T_{cr}$) and an increased risk of heat-related illnesses (Sherwood and Huber 2010; Kenney et al. 2004).

A widely used experimental approach to identify these critical thresholds is the *humidity ramp protocol* (also known as the *thermal-step* or *core temperature inflection-point protocol*), first introduced by Belding and Kamon (1973). In its classical form, this method progressively increases relative humidity in fixed increments—typically 1 mm Hg every 10 minutes—following an initial 60-minute core temperature stabilization period at a constant air temperature and low humidity (Kamon 1976). The point at which $T_{cr}$ rises uncontrollably is interpreted as the transition from compensable to uncompensable heat stress. Recent studies have adopted modified versions of this approach to determine CELs across populations and environmental conditions (Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023). However, reported humidity-ramp protocols differ substantially in their initial stabilization durations, step magnitudes, and ramp rates. For instance, some studies implemented a 30-minute stabilization phase followed by either a 1 mm Hg increase in ambient water vapor pressure or a 3% increase in relative humidity every 5 min (Cottle et al. 2022; Vecellio et a. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023), whereas others employed 1 °C ambient temperature or 1 mm Hg increments every 10 min (Belding and Kamon 1973; Kamon 1976). More recently, Meade et al. (2024) adopted a 70-minute equilibration period followed by 3% RH (i.e., ~1.85 mm Hg) increments every 10 minutes.

Despite broadly similar participant characteristics and testing protocols, reported CELs vary markedly, ranging from approximately 26 °C to 33 °C in young adults with metabolic rates of 1.3-1.5 METs (Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023, Meade et al. 2024). Such wide variability raises a fundamental methodological concern: does the arbitrary selection of ramp rate and step duration influence the accuracy of the predicted critical environmental limits?

The traditional ramp approach implicitly assumes that the human thermoregulatory system equilibrates to each environmental step before the next begins. In practice, however, the dwell time per step—typically 5–10 min—may be insufficient for the body to achieve a new steady state, particularly under conditions of high thermal inertia. This raises an essential question: does the observed inflection in $T_{cr}$ truly represent the physiological onset of uncompensable heat stress, or merely a transient lag—a dynamic mismatch between the body's actual thermal state and its moving equilibrium?

To address this, we hypothesized that the apparent inflection point in $T_{cr}$ during humidity ramp protocols is influenced by the duration of each step. Specifically, shorter steps may induce a premature and distorted onset of uncompensable heat stress due to incomplete thermal equilibration, whereas longer steps allow near full stabilization, yielding more accurate steady-state estimates. To test this hypothesis, the present study examines how stepwise duration affects the apparent critical inflection point in $T_{cr}$ during humidity ramp protocols. By systematically varying the rate of humidity increase under constant dry-bulb temperature conditions, we aim to elucidate how the temporal structure of the humidity ramp affects the transition to uncompensable heat stress. Furthermore, we introduce a simplified first-order thermal response model to describe $T_{cr}$ dynamics in relation to environmental humidity. Through this combined empirical-modeling approach, we aim to clarify how ramp timing distorts apparent critical limits and to propose evidence-based guidelines for designing physiologically valid humidity ramp protocols.

## Methods

### *Model derivation and assumptions*

The temporal evolution of core temperature ($T_{cr}$) during progressive humidity changes was derived from the first principles of whole-body heat balance. The human body is modeled as a single, lumped thermal compartment that exchanges heat with the surrounding environment via convection, radiation, and evaporation. At any time $t$, the rate of body heat storage equals the rate of metabolic heat production minus the combined dry (convective and radiative) and evaporative heat losses (Gagge and Gonzalez 2011)

$$C\frac{dT_{cr}}{dt} = \dot{M} - \dot{W} + \dot{Q}_{res} - \dot{Q}_{skin} \qquad \text{Eq.(1)}$$

where, $C$ is the effective whole-body heat capacity (J/°C); $\dot{M}$ is metabolic heat production rate (W); $\dot{W}$ is external mechanical work rate (Watt; $\dot{W}$≈0 watt under seated conditions); $\dot{Q}_{res}$ and $\dot{Q}_{skin}$ are respiratory and skin heat exchange rates (W), respectively.

The net heat loss through the skin surface can be expressed as the sum of convective, radiative, and evaporative fluxes (Gagge and Gonzalez 2011)

$$\dot{Q}_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} \qquad \text{Eq.(2)}$$

with $\dot{Q}_{conv} = h_c A_s (T_{sk} - T_a)$, $\dot{Q}_{rad} = h_r A_s (T_{sk} - T_r)$, and $\dot{Q}_{evap} = h_e A_s (p_{sk} - p_a)$

where, $h_c$, $h_r$, and $h_e$ are the convective, radiative, and evaporative heat transfer coefficients (W/m²/°C), respectively; $A_s$ is body surface area (m²); $T_{sk}$ is mean skin temperature (°C); $T_a$ and $T_r$ are ambient air (dry-bulb) and mean radiant temperatures(°C), respectively; $p_s$ and $p_a$ are the water vapor pressures at the skin surface and in ambient air (Pa), respectively.

Under the classical humidity ramp experimental conditions—where air temperature is held constant and relative humidity progressively increases—metabolic heat production ($\dot{M}$) and respiratory heat exchange ($\dot{Q}_{res}$) can be treated as approximately constant. Consequently, variations in total heat loss are primarily governed by humidity-dependent changes in the potential for sweat evaporation (Brebner et al. 1958; Clifford et al. 1959). To obtain a tractable representation of the system's transient thermal response, the net heat exchange was linearized around the steady-state operating point:

$$\dot{M} - \dot{W} + \dot{Q}_{res} - \dot{Q}_{skin} \approx -k[T_{cr}(t) - T_{cr,eq}(t)] \qquad \text{Eq.(3)}$$

where, $T_{cr,eq}$ is the equilibrium core temperature that would be achieved if the environment were held constant indefinitely (°C). $k$ is an effective whole-body heat transfer coefficient (W/°C)—the lumped sum of convective, radiative, and evaporative heat conductances, modulated by physiological control of skin blood flow and sweating. Mathematically, $k$ represents how efficiently excess body heat is dissipated when $T_{cr}$ exceeds equilibrium, which is read as:

$$k = -\left.\frac{d(\dot{M} - \dot{Q}_{loss})}{dT_{cr}}\right|_{eq} \qquad \text{Eq.(4)}$$

where, $\dot{Q}_{skin}$ denotes the sum of convective, radiative, evaporative, and respiratory heat losses, i.e., $\dot{Q}_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{res}$.

Substituting Eq.(3) into the whole-body energy balance [i.e., the Eq.(1)] yields

$$C\frac{dT_{cr}(t)}{dt} = -k\left[T_{cr}(t) - T_{cr,eq}(t)\right] \quad \text{Eq.(5)}$$

This relation shown in Eq.(5) indicates that the rate of core temperature change is proportional to the instantaneous deviation from the environment-defined equilibrium value.

Dividing both sides of the Eq.(5) by $C$ and defining the time constant $\tau = \frac{C}{k}$ gives

$$\frac{dT_{cr}(t)}{dt} = -\frac{1}{\tau}\left[T_{cr}(t) - T_{cr,eq}(t)\right] \quad \text{Eq.(6)}$$

The thermal time constant $\tau$ characterizes the rate at which $T_{cr}$ approaches equilibrium following an environmental step change. Eq.(6) describes a linear first-order low-pass response with time constant $\tau$ that encompasses both passive body heat storage and active thermoregulatory feedback. The time constant $\tau$ represents the characteristic response time for $T_{cr}$ to approach a new equilibrium following an environmental step change in relative humidity (RH).

During each discrete humidity step of duration $\Delta t$, the equilibrium temperature $T_{cr,eq}$ is assumed to remain constant. The analytic solution of Eq.(6) for a step initiated at time $t = t_n$ is given by

$$T_{cr}(t) = T_{cr,eq,n} + \left[\left(T_{cr}(t_n) - T_{cr,eq,n}\right) \times e^{-\frac{(t-t_n)}{\tau}}\right] \quad \text{Eq.(7)}$$

At the end of each step ($t_{n+1} = t_n + \Delta t$):

$$T_{cr,n+1} = T_{cr,eq,n} + (T_{cr,n} - T_{cr,eq,n}) \times e^{-\frac{\Delta t}{\tau}} \quad \text{Eq.(8)}$$

Eq.(8) quantifies how far the body approaches equilibrium within each step. If $\Delta t$ is sufficiently small, Eq.(8) can be approximated using the Euler form (Stewart 2015)

$$T_{cr,n+1} \approx T_{cr,n} + \frac{\Delta t}{\tau} \times (T_{cr,eq,n} - T_{cr,n}) \quad \text{Eq.(9)}$$

When the environmental humidity change is rapid (i.e., $\frac{\Delta t}{\tau} \ll 1$), the system (i.e., human body) does not equilibrate between steps, and residual thermal disequilibrium accumulates, expressed as

$$\left.\frac{dT_{cr}}{dt}\right|_{n+1} > \left.\frac{dT_{cr}}{dt}\right|_{n} \qquad \text{if} \quad \frac{\Delta t}{\tau} \ll 1 \quad \text{Eq.(10)}$$

where, $\left.\frac{dT_{cr}}{dt}\right|_{n+1}$ and $\left.\frac{dT_{cr}}{dt}\right|_{n}$ denote slopes of the core temperature change at the ($n$+1)th and $n$th step of a humidity ramp. It can therefore be deduced from Eq.(10) that the progressive acceleration in $T_{cr}$ rise results in an apparent inflection, which reflects dynamic lag rather than true uncompensable heat stress. Detailed mathematical justification can be found in Supplemental Material.

## Physiological verification study

### *Sample size and power calculation*

The primary comparison focused on differences in ambient partial water vapor pressure ($P_{air}$) at the inflection point of core temperature ($T_{cr}$) between the aggressive-ramp and slow-ramp protocols. Assuming a large expected effect size (Cohen's $d$ = 0.8) and a paired-samples $t$-test, a minimum of 12 participants was required to achieve 80% statistical power at a two-tailed significance level of 0.05. This calculation assumed low within-subject variability in $P_{air}$ at the point of $T_{cr}$ inflection point. To account for potential attrition, fourteen participants were ultimately recruited.

### *Participants and ethical approval*

Fourteen healthy young males (age: 23.5±1.8 yrs, height: 1.74±0.05 m, weight: 69.5±7.9 kg, body surface area: 1.83±0.12 m$^2$, body mass index: 22.9±2.0 kg/m$^2$), all nonsmokers and free from cardiovascular, metabolic, or thermoregulatory disorders, volunteered for this study. Written informed consent was obtained from all participants prior to testing. The study was approved by the Institutional Review Board (IRB) of Xi'an University of Science and Technology (Approval No. XUST-IRB225034) and conformed to the principles of the Declaration of Helsinki.

### *Experimental design*

Upon arrival, participants provided a urine sample to assess hydration status. Testing commenced only if urine specific gravity (USG) was ≤1.020, indicating euhydration (Oppliger et al. 2005). Participants with USG values above this threshold consumed an isotonic electrolyte solution and were re-tested until euhydration was achieved. Prior to chamber entry, participants confirmed a thermoneutral perception across all body regions, and their initial rectal temperature ($T_{cr}$) was required to be ≤ 37.1 °C. These procedures ensured that all trials began under comparable baseline hydration and thermal states.

Each participant completed two trials (slow-ramp and aggressive-ramp) in a randomized, counterbalanced order, separated by at least one week. All experiments were conducted in a climate-controlled chamber maintained at a dry-bulb temperature of 42 °C. Participants remained seated throughout and engaged in light office tasks (e.g., reading, typing) to simulate minimal metabolic heat production. In the aggressive-ramp protocol, ambient relative humidity (RH) was initially set at 28% for 30 min, followed by a 2% RH increase every 5 min until a termination criterion was reached. In the slow-ramp protocol, participants first underwent a 4-hour equilibration phase at 40% RH, after which RH increased by 6% per hour from the 4th to 6th hour, and by a 3% per hour thereafter until termination criteria were met. **Figure 1** presents a schematic overview of the two humidity-ramp protocol regimens used in this study and observed wet-bulb temperatures during the two ramp protocol regimens.

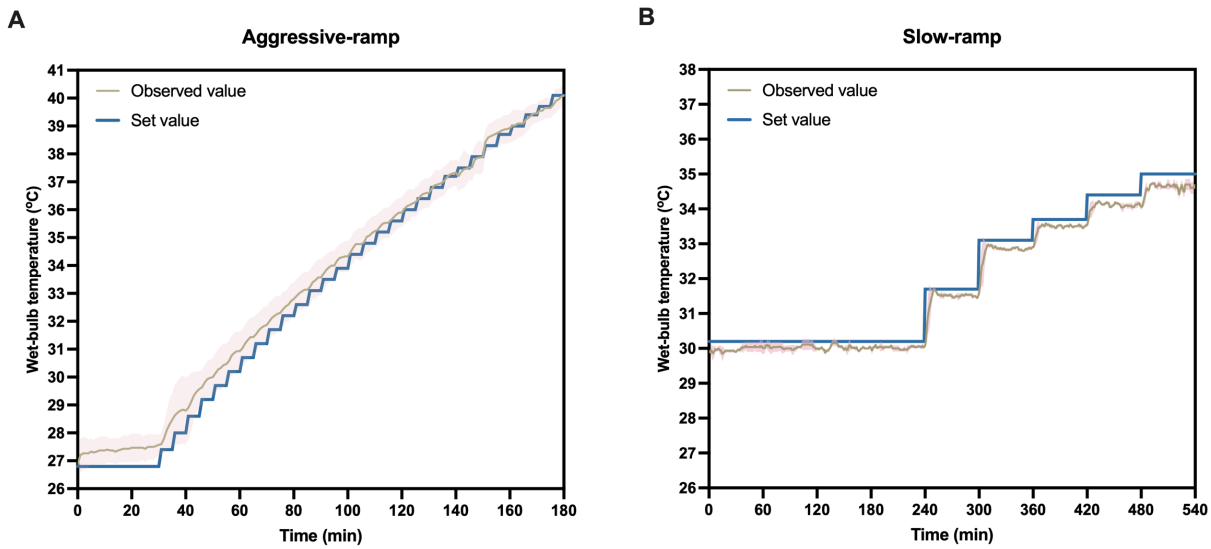


**Figure 1** Schematic illustration of the two humidity ramp protocols. **A**, *Aggressive-ramp*: an initial 30-min stabilization at 42°C, followed by 2% RH increments every 5 min until 88% RH (total exposure duration = 180 min); **B**, *Slow-ramp*: an initial 4-hour stabilization at 42°C and 40% RH, followed by 6% RH increments per hour for 2 h (to 52% RH) and then 3% RH increments per hour for up to 3 hours (to 61% RH; total exposure duration = 9 h). The programmed set values (blue lines) and the observed mean wet-bulb temperature with standard deviation (tan line with pink band) are shown for each protocol.

### *Measurements*

Hydration status was determined using a digital hand-held refractometer (PAL-1, Atago Co. Ltd., Tokyo, Japan; accuracy: ±0.2%). Rectal temperature ($T_{cr}$) was measured using a YSI-401

probe (YSI Inc., Yellow Springs, OH) inserted 10 cm beyond the anal sphincter. Mean skin temperature ($T_{sk}$) was obtained using iButtons (DS1992L, Maxim Integrated, Sunnyvale, CA; calibrated to accuracy: ±0.2 °C) affixed at the chest, upper arm, thigh, and calf, weighted according to Ramanathan's four-site equation (Ramanathan 1964). Heart rate (HR) was continuously recorded using chest-strap telemetry (Polar Vantage XL, Polar Electro Oy, Finland). Metabolic rate was assessed using a breath-by-breath metabolic system (Calibre Biometrics, Wellesley, MA) for 10 minutes after a 15-minute thermal stabilization period during which participants performed light office tasks in the heat chamber (Van Hooren et al. 2024). Perceptual ratings of thermal sensation, thermal discomfort, skin wetness, and thirst were obtained every 5–10 min using validated scales (**Figure S1**; Wang et al. 2025a). Environmental conditions (dry-bulb temperature and RH) were monitored continuously using three calibrated temperature–humidity data loggers (TH42W-EX, Huahanwei Technology Co. Ltd., Shenzhen, China; temperature accuracy: ±0.1 °C; humidity accuracy: ±1.5%). The loggers were positioned at heights of 0.1 m, 0.6 m, and 1.1 m above the floor. Core and skin temperatures and heart rate were logged at 1-minute intervals throughout all trial phases.

### *Termination criteria*

Trials were immediately terminated if any of the following occurred: 1) $T_{cr} \geq 38.6$ °C; 2) onset of heat-related symptoms (e.g., numbness, dizziness, nausea, or presyncope); or 3) voluntary withdrawal. Environmental adjustments were immediately halted upon termination, and participants were promptly removed from the heat chamber for recovery.

### *Data analysis*

Individual $T_{cr}$ were smoothed using the *smooth* function, with a smoothing parameter (*spar*) set at 0.9. The time derivative of $T_{cr}$ (°C/h) was computed to identify inflection points corresponding to the onset of uncompensable heat stress. The critical humidity limit was defined as the environmental condition at which $T_{cr}$ exhibited a sustained positive acceleration. Comparisons between the two humidity-ramp protocols assessed whether shorter dwell intervals produced systematically lower apparent critical limits. Because each participant completed both protocol trials, differences in critical wet-bulb temperature ($T_w$) between protocols were analyzed using a paired sample t-test, with effect sizes expressed as Cohen's *d*. All statistical analyses were conducted in R version 4.5.1, with significance accepted at $P < 0.05$. Data are presented as means ± SD (standard deviation) unless otherwise indicated.

### *Inflection point determination*

Earlier studies (Belding & Kamon 1973; Kamon 1976; Cottle et al. 2022; Vecellio et al. 2022; Wolf et al. 2021; Wolf et al. 2022; Wolf et al. 2023; Meade et al. 2024) identified the compensable–uncompensable transition visually from curvature in the core temperature trace. Although pioneering, this graphical approach relied on subjective judgment and was limited in reproducibility, particularly when $T_{cr}$ rose gradually or was affected by transient fluctuations. In the present study, the inflection point was defined objectively as the first time the smoothed $T_{cr}$ slope ≥ 0.25 °C/h and remained above this threshold thereafter. This criterion reduces subjectivity, enhances reproducibility, and aligns the detected inflection with the physiological onset of sustained uncompensable heat strain. To assess robustness, sensitivity analyses were performed using alternative thresholds (0.15, 0.20, 0.25, and 0.30 °C/h; see **Table S1** in Supplemental Material). Results confirmed that 0.25 °C/h provided stable and physiologically consistent estimates, whereas looser or stricter thresholds either advanced the transition unrealistically or delayed it toward higher core temperatures, potentially missing the early onset of uncompensable heat stress.

## Results

### *Physiological interpretation of the model*

The model conceptualizes the human body as a first-order dynamic system, governed by a single thermal time constant ($\tau$) that determines the rate of approach to thermal equilibrium. Two contrasting response regimes emerge depending on the relationship between the step duration ($\Delta t$) and the physiological time constant. When the dwell interval is short relative to the body's thermal inertia ($\Delta t \ll \tau$), core temperature fails to equilibrate at each new humidity level before the next increment. Consequently, residual deviations between the instantaneous equilibrium temperature and the actual core temperature accumulate over successive steps. This cumulative lag manifests as an apparent acceleration in $T_{cr}$ rise, producing an early inflection point that may be misinterpreted as a physiological limit of heat tolerance. Conversely, when the dwell interval is sufficiently long relative to the time constant ($\Delta t \gtrsim \tau$), $T_{cr}$ has adequate time to approach equilibrium within each step, minimizing transient deviations. Under these conditions, the temporal evolution of core temperature closely tracks the equilibrium trajectory, yielding a smoother and more physiologically representative response to incremental humid heat stress.

### *Empirical findings*

Critical environmental limits, expressed as wet-bulb temperature ($T_{w,critical}$), differed substantially depending on the duration of humidity increments ($\Delta t$). Core temperature increased most rapidly and reached critical levels earlier during the aggressive-ramp protocol than during the slow-ramp condition. Across 14 participants, the mean critical $T_w$ under the aggressive-ramp condition ($\Delta t$ =5 min) was 29.9±1.6 °C, whereas the slow-ramp condition ($\Delta t$ =60 min) yielded a significantly higher value ($T_w$ =33.4±0.5 °C; mean difference: 3.4±1.9 °C, see **Figure 2** and **Figures S2 & S3**). This divergence reflects the influence of thermal inertia on the apparent timing of physiological inflection. Consistent with the dynamic model, short ramp durations cause accumulated thermal lag, leading to an artificially early inflection in $T_{cr}$. In contrast, prolonged dwell intervals allow near-equilibrium, shifting the apparent critical threshold to higher $T_w$ values.

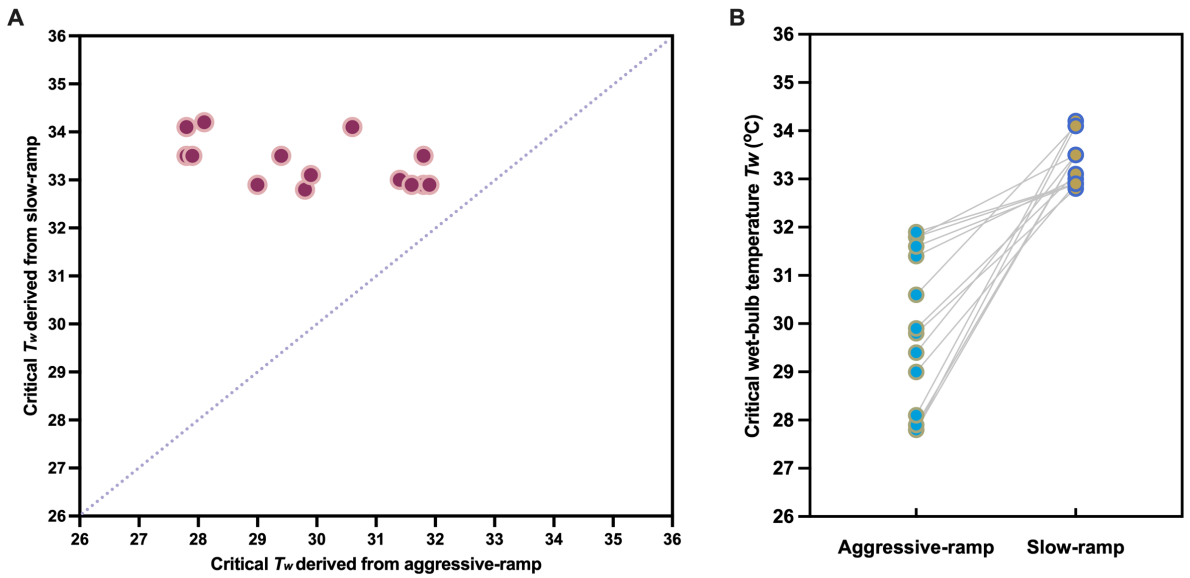


**Figure 2** Critical wet-bulb temperatures ($T_w$) thresholds determined using two humidity-ramp protocols (aggressive vs. slow) at a constant dry-bulb temperature of 42 °C. The purple dotted line represents the line of identity ($y = x$). Data points lie consistently above this line, indicating that the aggressive-ramp protocol systematically yields significantly lower critical limits than the slower-ramp protocol across all 14 participants (mean difference=3.4±1.9 °C, 95% CI [2.3, 4.5]; two-sided $P$<0.001) with a very large effect size (Cohen's $d$=1.93, 95% CI [0.91, 2.63], see Panel **A**). This systematic underestimation likely arises from the shorter ramp duration (2% RH increase per 5 min), which induces a premature inflection point compared with the slower protocol (60 min per 6%/3% increase). Panel **B** shows a matchstick plot comparing paired critical $T_w$ measurements from the two protocols. Each line connects the same participant's data under both conditions, with all lines trending upward from the aggressive-ramp to the slow-ramp values—clearly demonstrating that the aggressive-ramp protocol underestimates

the critical heat tolerance limit. The narrow distribution of slow-ramp data further indicates high measurement consistency, whereas the wider spread in the aggressive-ramp data suggests greater inter-individual variability and reduced precision under faster ramping conditions.

The time required for $T_{cr}$ to stabilize under constant ambient temperature conditions was empirically determined at two levels of relative humidity (RH) increment (3% and 10%), following an initial full equilibration of $T_{cr}$. **Figure 3** shows the temporal evolution of rectal temperature ($T_{cr}$) following a stepwise 3% or 10% increase in relative humidity (RH) at a constant ambient temperature of 42 °C. In **Figure 3A**, the representative participant achieved a re-stabilized core temperature approximately 141 min after the fifth 3% RH increase, following the initial stabilization period. Consistently, during the interval between 90 and 300 minutes, $T_{cr}$ required approximately 180 minutes to reach a steady-state (i.e., near 270 min; see **Figure 3B**). These observations indicate that, although the heat chamber achieved a 3% or 10% RH increment within 3–5 minutes, the physiological equilibration of $T_{cr}$ occurred much more slowly than previously assumed. Collectively, these findings demonstrate that conventional humidity-ramp protocols with 5–10 min step durations are insufficient for allowing $T_{cr}$ equilibration and may therefore underestimate the true critical environmental limits.

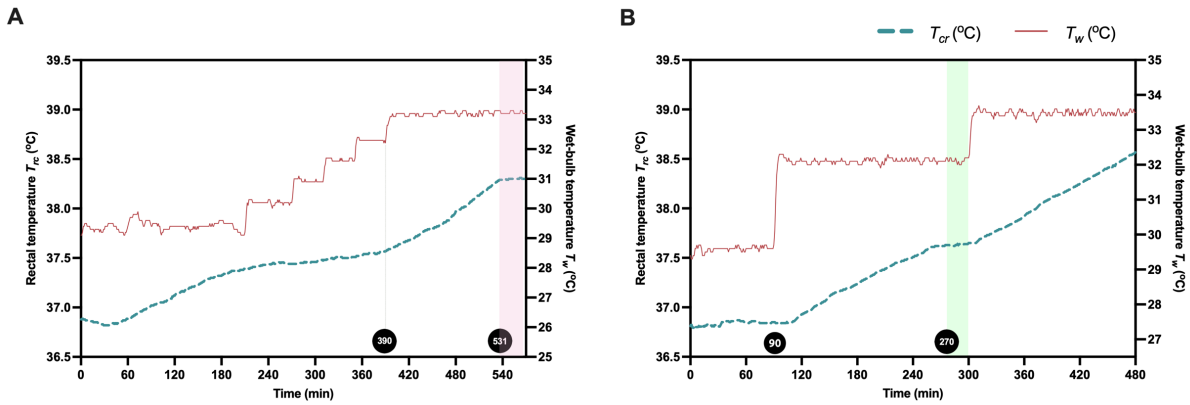


**Figure 3** Time ($\tau$) required for rectal temperature ($T_{cr}$) re-stabilization during stepwise increases in relative humidity (RH) following initial equilibration at a dry-bulb temperature of 42 °C. **A**, representative participant showing a 30-min stabilization period (shaded pink area) occurring at 531–570 min, after initial equilibration at 38% RH at 183 min, followed by five successive 3% RH increments. **B**, representative participant showing a 30-min stabilization period (shaded green area) occurring at 180 min, after initial equilibration at 38% RH, followed by a single 10% RH increase.

*Sensitivity analysis*

The first-order dynamical model highlights that the ratio $\Delta t/\tau$ (i.e., the ratio of step dwell time to the physiological time constant) determines whether $T_{cr}$ can approximate equilibrium at each stage. For $\Delta t/\tau \ll 1$, equilibration fails and residual deviations accumulate, yielding an apparent acceleration and early (premature) inflection in $T_{cr}$. This phenomenon constitutes a dynamic lag artifact rather than genuine evidence of physiological collapse.

Our empirically derived estimates of the core temperature time constant ($\tau$), obtained following an initial full equilibration of $T_{cr}$ in the humidity ramp approach, range from approximately 1.8 hours to more than 3 hours, depending on metabolic rate, hydration, and thermoregulatory efficiency. Consequently, step durations of 5–10 min used in many ramp-based studies likely place participants within the aggressive-ramp regime, where such artefacts are inevitable (Belding and Kamon, 1973; Kamon 1976; Vecellio et al., 2022; Wolf et al., 2022; Meade et al. 2024b). We therefore recommend empirical estimation of $\tau$ for each cohort, or alternatively, performing sensitivity analyses to verify the robustness of threshold estimates to plausible variations in $\tau$ values. **Table 1** presents the sensitivity of the dynamic response to step duration relative to the physiological time constant.

**Table 1** Sensitivity analysis of dynamic response to step duration ($\Delta t$) relative to physiological time constant ($\tau$)

| **Step duration ($\Delta t$, min)** | **Physiological time constant ($\tau$, min)** | | | **Predictive response characteristic** | **Artifact risk** |
|---|---|---|---|---|---|
| | **120** | **180** | **240** | | |
| 5 | 0.04 | 0.03 | 0.021 | Rapid environmental progression; core temperature lags markedly | High |
| 10 | 0.08 | 0.06 | 0.042 | Core temperature lags markedly; transient accumulation between steps | High to moderate |
| 60 | 0.5 | 0.33 | 0.25 | Partial or near equilibration for faster responders; moderate residual lag; slower for large $\tau$ | Low |
| 120 | 1.0 | 0.67 | 0.50 | Substantial or full equilibration across steps; minimal residual error | Very low |

Note: Artifact risk is categorized into four levels: **High** (substantial accumulation of lag between steps), **Moderate** (moderate lag with transient accumulation), **Low** (minimal lag and near steady-state equilibration), and **Very low** (no significant artifacts; full equilibration); The key determinant of dynamic distortion is the dimensionless ratio $\Delta t/\tau$, where $\Delta t$ represents the dwell duration and $\tau$ the physiological time constant of core temperature equilibration. Smaller values of this ratio indicate more rapid environmental progression relative to the body's thermal response. When $\Delta t/\tau \ll 1$ (e.g., 0.01–0.20), the environment changes faster than the thermoregulatory system can respond, leading to accumulated lag and an apparent early inflection in $T_{cr}$. When $\Delta t/\tau \approx 1$, full equilibration occurs and

transient effects are greatly reduced. When $\Delta t/\tau > 0.3$–$0.5$, the response effectively reaches near quasi-steady state, and dynamic lags and associated artifacts are largely eliminated.

## Discussion

This study demonstrates that the apparent "critical point" observed in humidity ramp protocols is strongly influenced by the temporal structure of the environmental change. Our first-order dynamic model shows that when a when the rate of relative humidity (RH) increase exceeds the body's intrinsic thermal response time (Cramer et al. 2022), the rise in core temperature ($T_{cr}$) accelerates across successive steps. Under these conditions, frequent small humidity increases force the body to continually "chase" a moving equilibrium, producing apparent inflection points that reflect dynamic lag rather than true thermoregulatory failure. Conversely, when each step is held long enough to permit partial or full equilibration, transient disequilibrium diminishes and the $T_{cr}$ trajectory becomes smoother and physiologically meaningful.

The ratio of step duration ($\Delta t$) to the thermal time constant ($\tau$) provides a dimensionless index of ramp adequacy. When $\Delta t/\tau \ll 0.2$, dynamic lag is pronounced, producing threshold-like artifacts; $0.2 \leq \Delta t/\tau < 0.5$ allows partial equilibration, and $\Delta t/\tau \gtrsim 0.5$ approximates quasi-steady-state conditions with minimal artifact. Empirically, a ratio of ~0.3 achieved stable core temperature responses without excessively prolonging exposure. Estimating $\tau$ from the initial equilibration phase enables individualized ramp pacing, while post hoc dynamic correction models may further approximate equilibrium $T_{cr}$ without substantially extending exposure.

Although the model simplifies the thermoregulatory system to a first-order system with a single time constant and linear heat transfer, it captures the essential dynamics linking environmental perturbations to physiological response delays. Real human thermoregulation involves nonlinear sweating kinetics, core–skin coupling, and feedback delays in vasomotor and sudomotor control (Wyss et al. 1974; McCook 1965; Bini et al. 1980; Taylor et al. 2019). Nonetheless, this first-order framework isolates the timing effect from higher-order complexities and provides a tractable, physiologically interpretable basis for refining ramp-protocol design in human heat tolerance research.

The classic formulation by Belding and Kamon (1973) emphasized the need for initial equilibration, noting that core temperature could require "more than 2 hours to stabilize" at

critical vapor pressure levels. To reduce the laborious nature of the full steady-state method, they adopted a shortcut approach, increasing humidity by ~1 mm Hg (≈2% RH at 42°C) every 10 minutes after an initial hour of equilibration. This approach acknowledged the necessity of equilibration upon chamber entry but did not extend the principle to subsequent humidity increments. As a result, the influence of continuous physiological equilibration on the determination of critical environmental limits was not fully appreciated. Our empirical data indicate that this assumption is invalid: even small humidity increases required approximately 2.35–3.0 h for $T_{cr}$ to restabilize (**Figure 3**). Hence, shortcut ramp protocols progress far faster than the body's thermal time constant, producing premature inflection points that do not reflect the true onset of uncompensable heat stress. Consistent with this, studies employing short dwell times (Vecellio et al. 2022; Wolf et al. 2022, 2023; Cottle et al. 2022; Meade et al. 2024) have reported $T_{w,critical}$ values of 26.0–32.3 °C in young adults—substantially lower than steady-state-derived thresholds (33–34 °C; Wang et al. 2025a).

Comparison between aggressive ($\Delta t$ = 5 min) and slow ($\Delta t$ = 60 min) ramp regimens provides further insight into accurately estimating CELs. The slow-ramp protocol yielded $T_{w,critical}$ =33.4 °C, aligning closely with physiologically inferred compensable–uncompensable boundaries, whereas the aggressive protocol underestimated the threshold due to thermal inertia. At 42 °C, a 3% RH rise increases $T_w$ by ~0.7 °C, sufficient to overshoot the narrow 33–34 °C transition band, highlighting the challenges of precise estimation without prolonged steady-state exposure.

A plateau substudy was initially planned to isolate transient thermal dynamics by maintaining each humidity step until $T_{cr}$ reached steady state (defined as $|dT_{cr}/dt| \leq 0.1$ °C over 30 min). However, this would have required > 10 hours of continuous exposure, posing ethical and logistical challenges (an illustration of this methodology is shown in **Figure S4**). Given prior evidence defining the compensable–uncompensable transition near $T_w$ =33–34 °C, the slow-ramp design provided a physiologically validated and practical alternative to exhaustive steady-state trials. Nonetheless, without prior knowledge of this range, designing a valid slow-ramp protocol remains challenging, as even small RH increments can produce disproportionately large changes in wet-bulb temperature at elevated dry-bulb levels.

## Physiological and methodological implications

We propose using the ratio $\Delta t/\tau$ as a dimensionless index of protocol adequacy, where $\Delta t$ is the dwell duration and $\tau$ is the physiological time constant for core temperature equilibration. When

$\Delta t/\tau < 0.2$, ramp protocols induce pronounced dynamic artifacts due to incomplete equilibration; $0.2 \leq \Delta t/\tau < 0.5$ allows partial equilibrium responses; and $\Delta t/\tau \geq 0.5$ denotes quasi–steady-state conditions with negligible artifact. Empirically, a ratio of ~0.3 was found sufficient to achieve stable core temperature responses without unduly prolonging exposure. Estimating $\tau$ from the exponential rise of $T_{cr}$ during initial equilibration enables individualized ramp pacing aligned with physiological response capacity, while post hoc dynamic correction models can further approximate equilibrium core temperature ($T_{cr,eq}$) without substantially extending total experimental time.

This framework explains why rapid humidity ramps consistently yield artificially low CELs and underscores the importance of standardizing ramp parameters across laboratories. Inflection-based thresholds should therefore be interpreted as transient, not steady-state, phenomena. Ultimately, prolonged steady-state exposures remain the benchmark for defining true compensability and for calibrating predictive models, occupational safety guidelines, and wearable heat-strain algorithms (Buller et al. 2018; Vanos et al. 2023; Xu et al. 2024).

The methodological implications are substantial. Traditional humidity-ramp studies assume sufficient equilibration between increments, yet our results demonstrate that typical 5–10 min steps are far shorter than the body's equilibration time. At $T_w \approx 31.7$ °C ($T_{db} = 42$ °C), $T_{cr}$ required > 4 hours to stabilize, and even a modest 3% RH rise demanded ~3 hours to achieve a new steady state (**Figure 3B**). Consequently, the apparent "inflection point" observed in ramp experiments primarily reflects cumulative transient heat storage rather than the true transition to uncompensable heat stress, producing artificially steep $T_{cr}$ trajectories and underestimation of human heat tolerance.

Thus, humidity-ramp protocols provide only a rapid, conservative approximation of compensability thresholds. To obtain physiologically valid estimates, each step must be maintained until steady-state conditions are at least partially achieved. Although time-consuming, this approach yields the most accurate representation of environmental compensability. Prolonged steady-state exposure therefore remains the methodological gold standard for quantifying human heat tolerance (Schlader et al. 2020; Wang et al. 2025a; Wang et al. 2025b).

## Limitations and future directions

The first-order model assumes constant metabolic rate and uniform body temperature distribution, which does not capture nonlinear sweating kinetics, core–skin gradients, or

feedback delays in vasomotor and sudomotor control. However, this simplification effectively isolates the dynamic lag mechanism central to this study. Future research should explore sex- and age-related differences in τ, effects of exercise intensity, and nonlinearities in evaporative efficiency at high humidity (Shoenfeld et al. 1978; Kenney and Munce 2003; Wang et al. 2025a). Extending the framework to diverse populations and integrating empirical and modeling approaches will enhance the physiological fidelity of heat stress thresholds and their application in predictive climate–health models.

## Conclusions

Humidity-ramp protocols have long served as practical tools for assessing human heat tolerance, but their validity is fundamentally constrained by thermal disequilibrium. When the rate of environmental change exceeds the body's capacity for physiological equilibration, apparent inflection points primarily reflect dynamic lag rather than true uncompensability. Critical environmental limits derived from short ramp durations should therefore be interpreted with caution. Accurate quantification of human heat tolerance requires either prolonged steady-state exposures or dynamic correction models validated against such reference conditions. Until these corrections are standardized, humidity-ramp protocols should not be used as stand-alone methods for defining physiological heat tolerance limits. Prolonged steady-state exposure remains the most reliable means to define the human heat tolerance limit and should continue to serve as the reference standard for future heat tolerance research.

## Author contributions

F.W. conceived the study, developed the model, designed experiments, prepared figures, acquired funding, and drafted the manuscript. Y.X. performed experiments, analyzed data, prepared figures, and revised the manuscript. H.W., M.C., X.H., and B.W. performed experiments, analyzed data, and revised the manuscript. All authors reviewed and approved the final version of the manuscript.

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## Conflict of interest statement

The authors declare no conflicts of interest, financial or otherwise.

## Data availability statement

Data are available upon request from the corresponding author (F.W.).

## Supplemental material

Supplemental material has been provided and uploaded to the peer review system.

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